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1.0 ABSTRACT

Vortex flows produced by submersibles typically unfavorably influence key figures of merit such as acoustic and nonacoustic stealth, control effectiveness/maneuverability, and propulsor efficiency/body drag. Sources of such organized, primarily longitudinal, vorticity include the basic body (nose and sides) and appendages (both base/intersection and tip regions) such as the fairwater, dive planes, rear control surfaces, and propulsor stators/tips. Two fundamentally different vortex control approaches are available (a) deintensification of the amplitude and/or organization of the vortex during its initiation process, and (b) downstream "vortex disablement." Vortex control techniques applicable to the initiation region (deintensification approach) include transverse pressure gradient minimization via altered body cross section, appendage dillets, fillets, and sweep, and various appendage tip and spanload treatments along with use of active controls to minimize control surface size and motions. Vortex disablement can be accomplished either via use of control vortices (which can also be used to "steer" the vortices off-board), direct unwinding, inducement of vortex "bursting," or segmentation/tailoring for enhanced dissipation. Paper includes submersible-applicable vortex control technology derived from various aeronautical applications such as mitigation of the wing wake vortex hazard and fighter aircraft maneuverability at high angle of attack as well as the status of vortex effects upon, and miti-

gation of, nonlinear control forces on submersibles. Paper concludes with specific suggestions for submersible-applicable vortex control techniques.

2.0 INTRODUCTION

“The security of our nation and the balance of world power depend on the submarine” (ref. 1). This security is dependent, first and foremost, upon submarine acoustic and non-acoustic stealth. Recent advances in the platform quieting area (e.g., ref. 2) have reduced the passive acoustic detection ranges to the point where other signatures, including various nonacoustic phenomena, become of concern and interest (e.g., refs. 3–5), particularly for the “shallow water” case. Many of these “unsound” phenomena, such as Bioluminescence, IR, internal waves, “wakes and scars,” etc., are either related to, or exacerbated by, organized longitudinal vorticity. These vorticity fields are produced by the platform at multiple sites, interact in the near field, and then undergo subsequent far-field interaction with the doubly stratified (thermal, salinity) sheared and turbulent water column (refs. 6–14). Depending upon platform depth, strength and configuration of these vorticity fields, and conditions in the ambient water column, the resulting disturbances can possibly be detected by, for example, space/air/ship borne IR, optical, radar, microwave, or laser sensors.

In addition to the nonacoustic detection issues, platform generated organized vorticity production and interaction can also severely impact other important figures of merit such as controllability and maneuverability (ref. 6, 15), passive acoustic signature, body drag, and propulsor efficiency and vibration. Platform sources of organized longitudinal vorticity include the body (nose and sides), various appendages (both bases/intersections and tips) such as the

fairwater, fairwater or bow planes, and rear control surfaces and propulsor components including stator-generated and propeller tip vortices. It is therefore obvious that vortex “control” would be beneficial to several measures of platform effectiveness and efficiency. Such control can be applied/exercised either in the vortex initiation process or in the near field interaction regions downstream of initiation. The former is probably the approach of choice while the latter is a particularly useful ploy/fix for existing problems and/or residual vorticity remaining after initiation region treatment. Historically, research in the vortex control area has focused primarily upon various aeronautical applications such as wind-tunnel flow management (ref. 16), wing tip vortex control for mitigation of the wake vortex hazard (e.g., ref. 17), drag-due-to-lift reduction and stealth, and, more recently, control of body vortices for improved maneuverability (refs. 18 and 19). By and large, this technology has not yet been extensively applied to submersibles. A control issue is the requirement for the control vs. portion of the vortex controlled, i.e., for acoustic stealth and maneuverability/control surface effectiveness, one can either “steer” the vortex away or alter the inner core, whereas for non-acoustic far field issues the large-scale circulation should, in general, be diminished.

The purpose of the present paper is to review and discuss the status of the various vortex control options available to the platform designer and to suggest approaches which appear feasible on the basis of submarine performance issues including nonacoustic and acoustic stealth, controls optimization, vibration minimization, improved propulsor efficiency, and minimal drag increase/drag reduction, considering the operational range of vehicle attitude/motions. Emphasis is placed upon control in the vorticity origination and near field interaction regions. The far field

interactions with the water column are not discussed herein, although an obvious control ploy in that regard is to operate in regions of strong ambient turbulence (ref. 20, 21). The submarine far field vortex wake—ambient flow interaction problem has been the subject of intense research for years. However, the submarine body/appendage vortex production and near field interaction region has not yet been adequately addressed from a vortex control viewpoint. Much of the far field work has focused upon analysis of vortical fields produced by current designs rather than attempts to mitigate/control body-generated vorticity. Other naval applications of vorticity control include wake minimization for surface ship stealth, bilge vortex reduction for drag and propulsor optimization (ref. 22), and sonar array self-noise mitigation as well as acoustic treatments for machinery (internal flows).

3.0 OVERVIEW OF LONGITUDINAL VORTEX PHYSICS AND CONTROL ISSUES

At the outset of this discussion it should be noted that, for submarines, there are two rather different problems to be addressed in relation to vortex control.

First, there is the problem of vorticity production by the submarine while it is operating in a very stealthy manner. In this case control action should be a minimum and body angles must be kept as small as possible. For this mode of operation, the submarine designer should be able to use all the power of the methods of linear hydrodynamics and boundary-layer theory to achieve a design creating minimum vorticity. If some aspect of the flow around a submarine in this condition must be treated by nonlinear interactive methods, a fundamental design mistake has been made.

Second, there is vorticity production when the submarine must be maneuvered. In this case,

strong trailing vorticity patterns must be generated for there is no force without there being a cross-stream moment of trailing vorticity. When treating the effects of such vorticity, especially the mitigation of such effects, it is almost always necessary to consider the nonlinear interaction of such vorticity. A knowledge of these nonlinear interactions is essential to the submarine designer if he is to understand controllability and control effectiveness or he is to design vehicles that do not produce bothersome organized vorticity as a result of desired control forces and moments.

Detailed treatments of vorticity dynamics (refs. 23–27, 21a) indicate that the dominant source of longitudinal vorticity production for submersibles is transverse pressure gradients. Such gradients occur, for example, about bodies at incidence or yaw and near the intersection and tip regions of appendages (ref. 28). Therefore the zeroth-order approach to longitudinal vortex control is to minimize these transverse pressure gradients and/or institute 3-D separated flow control techniques. For the body itself, such a vortex control approach (minimization of transverse pressure gradients) can be accomplished by (a) altering basic body geometry, (b) ensuring continuous body curvature (continuous 2nd derivatives) (ref. 29), and (c) minimizing body motions, via, for example, use of active control systems to account for variations in body buoyancy along the “flight path.” Similar approaches can also be employed for appendages, i.e., fillets and dillets in intersection regions (alter basic geometry) and use of active controls to minimize required control surface motions. Probably the most straightforward method of vortex control for appendages is to simply eliminate (or at least minimize) the size of the protuberance, e.g., by folding the device into the body when not in use. This latter approach is used by various species of nektons (refs. 30–32). Elimination of the submarine fairwater has been suggested

probably ever since one was first employed, and this may even be feasible in the future due to the development of deployable off-board sensors. Also, use of thrust vectoring for control may allow control surface size reductions.

Once the longitudinal vorticity is produced, its subsequent near field behavior is influenced by its turbulence structure and interactions with body flow field elements (pressure gradients, the propulsor), adjacent surfaces, and/or other vortical entities. The turbulence structure of longitudinal vortices is affected to first order by the flow-induced curvature within the vortex which stabilizes the fluctuation fields in the inner portion (refs. 6, 7, 33, and 34) leaving in many cases an annular ring of turbulence. This stabilization can be mitigated by local turbulence production within the inner region by radial gradients of the axial flow and therefore the near field development of longitudinal organized vortical entities is a function of the detailed initial mean 3-D vorticity structure of the vortex, which in turn is dictated by the body/appendage/propulsor geometry and motions.

Conventional wisdom (e.g., ref. 35) indicates that longitudinal vortex dynamics are not sensitive to Reynolds number. This is based primarily upon an observed Reynolds number insensitivity of (pressure-gradient-induced) vortex bursting in the lee-surface flow of delta wings. Detailed vortex development and thus local characteristics can, however, be quite sensitive to vortex Reynolds number (refs. 36–44), and there is a significant shortfall between full-scale submarine Reynolds numbers and those attainable in most (water and air) test facilities. Facilities with Reynolds numbers approaching those of deployed platforms include (a) NASA LaRC National Transonic Facility (NTF) (cryogenic nitrogen), (b) sub (but large) scale pop-

up bodies and, perhaps in the future, a liquid helium (I) tunnel currently under study at the University of Oregon by Prof. Russell Donnelly. In the absence of tests in these facilities, and in light of the current uncertainties in turbulence modeling for organized vortical flows (ref. 45), diagnosis and treatment of longitudinal vortices on submarines is an inherently uncertain business in view of the known (and largely unknown) Reynolds number sensitivities involved. In fact, this Reynolds number shortfall was at least partially responsible for the difficulties which NASA encountered in the '70's in extending vortex control approaches from ground facilities to flight tests (on 747 aircraft) in what is probably the largest vortex control program ever undertaken, attempts to mitigate the lift-induced wake vortex hazard to following light aircraft produced by the introduction of "heavy" (DC-10, L-1011, 747) transport aircraft.

There are four disparate approaches to longitudinal vortex control for submersibles: (1) reduce initial vortex production/strength via minimization of transverse pressure gradients, (2) counteract/annihilate the organized vortex motion by producing vorticity of the opposite sign, either in the initiation region or downstream which can be accomplished by blowing, strakes or moving surfaces, (3) attempt to spread/reduce the intensity of the organized vorticity via segmented/tailored generation, turbulence interactions, or excitation of instabilities/bursting, and (4) generate/utilize "control vortices" to steer the organized vortical motion, away from interactions with (a) platform surfaces (for vehicle control/acoustic stealth) and (b) the air-sea interface (for non-acoustic stealth). The balance of the paper will discuss implementation approaches of these various techniques for the basic body, appendage intersection regions, and tip flows, as well as off-board but near field vortex interactions and control.

4.0 BODY VORTEX INITIATION AND CONTROL

As stated in the previous section, angles of attack or sideslip on nominally axisymmetric submarine configurations induce transverse pressure gradients which, for surprisingly small angles, can produce organized longitudinal vorticity (ref. 46). It was also pointed out that the zeroth-order vortex control approaches for the body generated vortex flows include body shaping to minimize transverse pressure gradients (particularly beneficial if the prevalent body motions occur in a particular direction), use of continuous curvature surfaces to minimize pressure gradients, utilization of 3-D flow separation control techniques, and minimization of body motions via automatic control systems. Such body shaping could be either implemented as fixed changes to the body cross section(s) or via movable (e.g., inflatable) localized panels analogous to the "mission-adaptive" wing approach in aeronautics. For the low to moderate incidence case (e.g., $\lesssim 0(20^\circ)$ (ref. 47)), direct control during vortex initiation is possible using suction (ref. 48) injection (refs. 49–52) and perhaps moving surfaces. The key problem for such "active" submarine body vortex control approaches as local body (Re)-shaping, injection, moving surface, etc., is the variation in vortex initiation locus induced by variations in body pitch-yaw motions. An alternate control technique, albeit one with an innate drag penalty, is the use of "control" vortices or surface interactions to cancel, via adjacent (same sign of vorticity) or direct (opposite sign of vorticity) "unwinding," of the developing body vorticity (refs. 53–58). The basic approach is to produce and introduce vorticity with sign either opposite or equal to that produced by the body (depending upon proximity of the control and controlled vortical systems). Such control vortices could be generated by deploying either conventional vortex generators or use of water jets. This technique also has the problems associated with variability in body

vortex initiation location (a function of detailed body motion) and introduces additional drag and other force vectors into an already messy problem. However, if the body vortex must be dealt with/alterd, such a technique does constitute an alternative approach.

Characteristics of (mainly missile) body vortical systems are discussed and documented in, for example, references. 43, 46, 47, and 59–72 with ref. 47 being probably the most useful in the present regard (provides vortex location, etc.). Additional information regarding vortex characteristics and control techniques (strakes, blowing, etc.) for high angle of attack/yaw, where asymmetric body vortices form and induce “side forces” is given in references 73–82.

In summary, submersible body vortices, induced by body pitch/yaw motions, are controllable via minimization of such body motions (at cruise) through use of active controls, mitigation of local transverse pressure gradients by geometrical modifications, and blowing to reduce the initial vortex strength and strake or water jet generation of “control vorticity” to “unwind” the vortical motion. The directional variability of submarine body motions necessitates that such systems be active, dispersed, rapidly deployable, and triggered by distributed sensors. Such vortex control systems of sensors and actuators or effectors could be compatible with double hull submarine construction. These approaches might be aided by provision of “discrete” body discontinuities to aid body vortex localization and perhaps provide vortex segmentation and/or tailoring for enhanced turbulence productivity.

5.0 VORTEX CONTROL FOR APPENDAGE INTERSECTION REGIONS

Considerable numerical and experimental research conducted over the last 10 years has carried us beyond the status of protuberance intersection flow knowledge circa 1977 when “the

formation, size, strength, and extent of the vortices and the mechanisms of interaction among the vortices in front and around the obstacle are virtually unknown” (ref. 83). Intersection flow physics is of concern in many applications including wind engineering and boundary-layer meteorology (refs. 83–85), ocean engineering (ref. 86), gas turbine and other rotating machinery design (ref. 87), heat exchangers and wing/empennage body intersections as well as for submarine-appendage (sail, control surfaces) intersections. The basic flow structure produced by intersection regions has now been studied in considerable detail (refs. 83–104 and references cited therein). The essential flow feature is a horseshoe vortex which forms in the nose-to-midchord region and trails downstream, in some cases for “hundreds of boundary-layer thicknesses” (ref. 88). This vortex is formed by the transverse pressure gradients induced by the obstacle/appendage flow field. The trailing intersection-induced longitudinal vorticity for a symmetric slender appendage can consist of either symmetric or asymmetric vortex systems, depending upon flow incidence. Also, the main vortex usually engenders subsidiary vortex systems which can dynamically interact, the number and relative steadiness of such protuberance-induced nested vortex systems is a function of the protuberance geometry, Reynolds number, etc. Downstream the asymmetric vortex systems suffer less mutual annihilation and are consequently longer-lived. Contemporary CFD is capable of resolving the juncture problem numerically and providing estimates of the general flow phenomena (refs. 105–110). Although the detailed transition and turbulence physics required for accurate predictions are not yet in hand, these codes can be, and have been (e.g., refs. 107–109), used to investigate/optimize vortex control approaches for juncture regions.

Since the vorticity to be controlled is produced by the appendage pressure fields, the most obvious, and among the most effective, appendage vortex control technique is to simply reduce the magnitude and extent of the basic perturbation, usually by reducing the appendage leading-edge diameter (refs. 111–117) or employing appendage leading-edge sweep (refs. 107 and 109) or a combination thereof. These are very powerful approaches and result in drastic changes in vortex strength.

Another popular appendage vortex control technique is the use of fillets, which decrease the local pressure gradients without (generally) altering the overall appendage-imposed pressure change. Fillets have long been used on an empirical cut-and-try basis to reduce appendage intersection drag. Much of this early work is summarized in Horner's book (ref. 118) and indicates that increasing the longitudinal fillet radius is favorable (for drag reduction) as is extending the fillet beyond the trailing edge of the appendage (refs. 118 and 119). More recent work regarding fillets (refs. 107, 108, 120–129) has included detailed flow field studies aimed at determining the influence of such juncture "fairings" upon vortex generation and behavior, i.e., vortex control. This work indicates that even simplex leading- and trailing-edge fairings or fillets can provide significant mitigation of vortex strength and size. The fillet must, for the submersible case, be carried around the leading edge to account for operational variations in flow incidence. Also, reference 107 indicates that a fillet radius on the order of 3 times the leading-edge diameter is required to achieve a sizable effect on the vortex, which may explain the adverse effects found in reference 125 for a much smaller fillet (radius on the order of one-half the leading-edge diameter). There are still no general design guidelines for fillet optimization

in a given situation. CFD techniques allow analysis of a given shape but the optimization strategy has not yet been worked out, and the results would probably vary somewhat depending upon the ordering of the various figures of merit (non-acoustic/platform control/acoustics/drag, etc.), as well as whether the flow orientation changes operationally (as it does in a submarine). Of considerable interest are the results of reference 129 which indicate that even a triangular flat ramp in the intersection is of great benefit in vortex mitigation (perhaps due partially to production of “negative” vorticity at the edges of the ramp).

Two additional intersection vortex control techniques have been recently proffered. The first is the application of direct “unwinding” via impingement of the developed horseshoe vortex flow upon a set of vortex generators suitably orientated to cancel the incident vorticity (ref. 130). This is essentially the application of the work of references 53 and 54 to the intersection vortex problem, and while the technique works well, the operational variability of flow incidence/resultant vortex location probably precludes its use. The devices could be modified to generate adjacent “like sign” vorticity to achieve mutual vortex mitigation (ref. 54). This would provide a somewhat wider operational flow incidence envelope but probably not wide enough for successful application to submersibles.

The other “new” approach to the design of intersections comes under the heading of generalized “dillet” technology. Since the primary sources of the trailing vorticity seen in necklace vortices are the athwartship pressure gradients induced on the submarine hull by the application of the sail, one can shape the hull surface in the vicinity of the sail so as to eliminate these induced pressures. The required shape may be calculated using the negative image method.

The shape that results requires a depression or dent in the vicinity of the root of the sail rather than a fill or "fillet." Hence the term "dillet." At the present time, the methods used to design optimum intersections are in their infancy. One can calculate using the methods already developed the changes in interference drag that result from small changes of shape in the interaction region. Yet to be developed is an inverse design method that would allow a complete intersection shape to be designed to minimize integral measures of performance (for example, drag). The basic ideas behind dillet technology are ascribed to J. E. Yates and C. duP Donaldson (e.g., ref. 26) and, in the tests made so far, elimination of a major portion of the longitudinal vorticity associated with a thick airfoil mounted on a surface has been demonstrated. In regard to interpreting necklace vortex experiments, it should be kept in mind that the conventional necklace vortex is seen because the flow separates. If this separation had been prevented (by sucking off the boundary layer, for example), the longitudinal vorticity would still be produced because the lateral pressure gradients would still exist. This vorticity would not be observed directly unless the boundary layer separated downstream of the intersection, but it is there nevertheless. This is much the same as the vorticity due to lift on a wing which is not observed directly until the flow leaves the surface of the wing.

In summary, vortex control for appendage juncture regions is probably best accomplished by a combination of techniques which reduce the vortex strength in the initiation region. These include appendage leading-edge radius reduction in the intersection region (consistent with overall appendage function), appendage leading-edge sweep, some leading-edge filleting if required, and dilleting along the sides of the protuberance. As a matter of interest, most

appendage intersections in nature such as the dorsal fin-body attachment region on sharks are well-filletted (large radius fillet on front and sides) and generally swept with a small leading-edge radius.

6.0 TIP VORTEX INITIATION AND CONTROL

The crucial initial question concerning tip vortex strength/structure, etc., is the loading level and distribution over the associated appendage. Tip flows associated with appendages which are not carrying lift are essentially 3-D momentum wakes, possibly containing small-scale embedded longitudinal vorticity engendered by Görtler-like wake instabilities (ref. 131). The tip vortex control problem considered herein is associated with tip flows on lift-carrying appendages. For submarines this corresponds to the sail/bow planes (when activated/loaded), the sail itself (when the boat is maneuvering/sail is at angle of attack), the rear control surfaces (when loaded) and the propulsor tips. An obvious zeroth order vortex control technique for tip flows is to minimize the lift on the associated appendage, e.g., via active controls, greater solidity, larger diameter propellers, and sail profiles designed with reduced lift coefficient. The first order approach is to use an increased aspect ratio which for the same lift force reduces the vortex strength via a reduced lift coefficient and increased span.

The vast bulk of the research regarding tip vortex diagnosis and treatment/control stems from attempts to control the strong and highly organized tip vortices associated with large aircraft in the terminal area which can constitute a serious hazard to following lighter aircraft and thus limit airport productivity (ref. 132). In general this aircraft wing vortex problem differs from submarine tip flows in that during the critical aircraft takeoff and landing periods much of the

lift is carried on part span flaps and therefore the vortex (near wing) wake is actually a complex system of flap, wing tip, and other lesser vortex systems (whose interactions can actually be used for vortex control, as will be discussed later herein). In the submarine case the control surfaces, at least thus far, usually employ either full-span flaps or are all-movable surfaces and therefore the tip vortex is the major vorticity element (per appendage), as the appendage/body intersection vortices are generally contained within the body boundary layer.

Excellent summaries regarding wing tip/flap vortex flow physics are available, for example, in references 6 and 133–136. CFD is beginning to seriously address viscous details of the tip vortex formation problem (e.g., ref. 137), enabled by the capacity of the Cray 2 class machines. Detailed summaries of the extensive research aimed at tip vortex control for wake vortex hazard reduction on aircraft are available in references 6 and 138. The techniques which, to various extents, “work,” i.e., reduce the strength, diffuse, the core, etc., of tip vortices are grouped herein under the headings of (a) mass injection, (b) tip treatments, and (c) tailored vorticity production. Techniques which involve vortex—vortex interactions are addressed in the next section.

The mass injection technique is, in reality, four disparate approaches depending upon the direction of injection. Direct spanwise tip injection (refs. 139–142) provides an effective increase in span, reduced drag due to lift, and diminished tip vorticity, at least partially due to vortex segmentation (ref. 140). Downward directed tip injection (refs. 143 and associated patents, refs. 144–146) tends to directly counter the wing tip upwash which rolls up into the wing-tip vortex. Results in reference 143 indicates a sizable (0(40%)) reduction in vortex core strength with a concomitant increase in lift-to-drag ratio. For submarine applications the “lift vector” can

be in either direction depending upon body motions/required control power and therefore a dual action injection system would be required.

The third and fourth tip mass addition vortex control techniques are related in that both attempt to produce increased turbulence levels within the vortex to aid in vortex dispersion/dissipation. The first such technique is to direct the tip injection axially, either up or downstream to create a wake, or jet, respectively in the axial velocity component of the tip vortex. This generates a mean shear in the axial flow which can greatly augment total turbulence production in the vortex. This injection can be accomplished either by an auxiliary system (refs. 147–156) or directly by locating engines in the wing tip region (e.g., refs. 157–158). This is a powerful technique and has yielded consistently good results both as to vortex mitigation and impact (or lack thereof) upon basic wing flow. The fourth tip mass injection technique is to utilize tip jets at various orientations to “mix up the flow” and thereby augment/create additional turbulence. This is a less structured approach, but evidently fairly effective in promoting vortex dissipation. Various and diverse tip vortex systems are observed, i.e., vortex segmentation occurs as well as increased turbulence levels (some of the latter may, in fact, be due to dynamic multiple vortex motions/interactions) (refs. 159–163).

Still another tip vortex mitigation approach involves altering the wing (or appendage) spanload distribution to avoid formation of a concentrated vortex core (refs. 164–166), i.e., tailored vorticity production. This is accomplished via a saw-tooth or alternating spanwise variation of wing circulation. This approach has not been checked out experimentally to any major extent. Finally, there is a plethora of tip region “gadgets” which have been tried based

upon several control approaches. These include (a) blades (fixed or rotating) inserted into the (angled) tip vortex flow to recover thrust (fixed, ref. 167) or power (rotating, refs. 168, 169) from the tip flow and thereby partially disable the tip vortex, (b) fixed tip region fences (refs. 170, 171) to alter the vortex flow in a manner analogous to a honeycomb (see ref. 16), (c) an "OGEE" tip (ref. 172), and (d) porous (distributed passive bleed) tips (refs. 173–175). All of these devices "work" to some degree.

In summary, the bulk of the available vortex control technology and invention has historically centered upon the (aerodynamic) requirement to reduce the wing tip vortex hazard. The number of approaches which "work" is large and the issue of which one to apply to the submarine appendage tip vortex control problem can only be addressed in the context of which appendage/blade is being treated and for what reason (nonacoustics, acoustics, drag, etc.) in that a fix for one purpose may be detrimental to other figures of merit. The approaches discussed herein are relatively immature and considerable research is required, probably on several competing devices/approaches, before a "best" method is arrived at. However, many of these approaches are viable, what remains is to pick and choose and evaluate for the specific application (bearing in mind the previous comments herein concerning (largely unknown) Reynolds number effects). Axial injection, perhaps using the propulsion plant cooling water flow which must be ejected overboard in any event, does appear to the present authors to be particularly intriguing.

7.0 NEAR FIELD VORTEX CONTROL

Previous sections of the present report have considered various sources of organized vorticity (body, intersection regions, tip flows) and associated local control techniques. This section

addresses vortex control possibilities subsequent to vortex generation but still within the “near field” (before extensive interaction with the water column). Probably the most prevalent (perhaps even inadvertent) deployed vortex control technique for submersibles is to either allow, or tailor the flow to ensure, vortical flow interaction with the propulsor. This is obviously suitable for (a) vortices near the body at the aft end (small body vortices, intersection vortices), and (b) the nonacoustic stealth problem but can be extremely adverse from an acoustic point of view (e.g., ref. 176). Use of a shrouded “pump jet” propulsor which mitigates this acoustic problem significantly enhances the overall merit of the “vortex eating propulsor” as a viable vortex control technique. A free-wheeling device ahead of the main propulsor to correct maldistributions in propulsor in-flow might also be efficacious (e.g., ref. 177). A somewhat related approach, which is perhaps suitable for smaller vortical zones is to simply place the cooling water intakes such as to ingest the fluid continuing the vorticity into the interior of the ship.

The prime “off-board” but still near field vortex control technique is to consider the various vortex fields produced by the body in-toto and utilize them to either (a) unwind/counter, (b) diffuse/dissipate, or (c) steer each other to accomplish the desired result (improved control function, improved stealth, etc.). This method is made difficult by the variability of vehicle attitude, etc., and resulting alteration in vortex loci within the flow field. Additional and various “control vortices” can be generated (via vanes or jets) to account for this variability in vortex system configuration. Also, some vortices move less than others and therefore may be more amenable to such “off-board” control.

References 6 and 176, 179 provide the fundamental theoretical framework for vortex control

via vortex—vortex interaction and include first-order maps of multiple vortex behavior as a function of proximity and circulation ratio, e.g., whether “two vortex” sets will tend to merge or separate. Sources of “control vortices” can include loaded part span flaps (e.g., refs. 6, 180, the “in-board” vortex, being of opposite sign to the “tip vortices” can be of especial effectiveness in this regard (refs. 181, see also 179)). From reference 181, the flap vortex should be approximately the same strength as the tip vortex. Control vortices can obviously also be generated by devices specifically added for that purpose such as “fins” (essentially large “vortex generators” refs. 182, 183) or various other of the innately-generated body or appendage vortices. References 184 to 190 document experimental and theoretical studies of “off-board” vortex interactions, including viscous effects.

As stated previously, the mechanisms by which “control” vortices can be utilized to alter organized submersible vorticity are manifold and include: (1) “unwinding” or partial “destruction” via “negative” vorticity generated by a root/opposite “tip,” side of body (in lifting case) or control vortex production device, (2) “diffusion” of the vorticity across a broader region by reorganization and turbulence, induced generally by vortices of the same sign, (3) instability excitation (e.g., refs. 191–196), and (4) “simple” steering of the main vortex away from critical portions of the body or away from the free surface (air-water interface).

8.0 INTERACTION OF BODY VORTICES WITH THE STERN PLANES AND RUDDER

In the world of aircraft design, it is well known that, although one does one’s best to keep the tail of the airplane away from the vorticity shed by the lifting wing, the static and dynamic stability of the aircraft is greatly effected by the “downwash” of the wing. In the submarine

world the stern planes cannot be taken out of the “downwash” of the hull, so they must operate in a very strong field of trailing vorticity. Matters are made a great deal worse by the fact that the shedding of trailing vorticity by a hull even at small angles of attack ($\leq 10^\circ$) is very complicated. At small angles of attack, a submarine hull may have a net upward lift but this upward lift is the result of the bow section of the submarine lifting up somewhat more than the stern section lifts down. This can result, when the vorticity separates from the hull, in a very complex interaction as the trailing vorticity approaches the stern planes. Add to this the interaction of other vorticity that may come from the tip and root of the sail, as well as any bow or fairwater planes that may be generating forces, and one poses for oneself a very complicated nonlinear control problem (see for example, ref. 197, 198). At the present time, designers are attempting to sort these interactions out on existing shapes and designs. However, the authors believe that some of the undesirable features of the existing interactions might be mitigated by the use of pairs of small controls that produce equal and opposite forces (no net force) and whose equal and opposite trailing vorticity could greatly improve, through their nonlinear interaction with a given trailing vortex system, the control effectiveness of the stern appendages of a submarine.

9.0 CONCLUDING REMARKS

VORTEX CONTROL TECHNIQUES POSSIBLY APPLICABLE TO SUBMARINES

Fundamental vorticity control approaches include (a) minimization of initial vorticity production, primarily by mitigating transverse pressure gradients on the body (during maneuver/cruise in the inhomogeneous water column), and in appendage intersection and tip regions, (b) production/utilization of “counter vorticity” (vorticity with the opposite sign) to annihilate vorticity either as it is produced or downstream, (c) spread/diffuse the vorticity over a larger

area via control vortices, turbulence or excitation of instabilities, and (d) utilization of control vortices to “steer” the flow and therefore delay encounters with other vehicle elements and/or the air water interface.

Specific design features which the present authors believe would be efficacious and conducive to vortex minimization and mitigation include (NOTE: application a function of particular platform design details.):

1. continuous surface curvature (continuous 2nd derivatives) to minimize transverse pressure gradients
2. minimization of (a) appendage size and pressure loading and (b) vehicle and control surface motions
3. elevated (above the inner part of body boundary layer) and active (perhaps even ring wing) control surfaces to minimize body and control surface loading and motions
4. retractable/folding/deployable appendages
5. thrust vectoring (perhaps via use of segmented circulation control on stators for pump-jet propulsor configurations)
6. free-wheeling device ahead of propulsor to minimize inflow distortion/vortex influence
7. use of fillets, dillets, sweep, and leading-edge minimization on appendages to reduce transverse pressure gradients/intersection vortex production/drag

8. tip blowing, perhaps using cooling water which must be vented overboard (unless this enhances IR scarring) to dissipate tip vortices
9. use of inboard secondary vorticity to control tip vortices, especially on horizontal control surfaces to reduce vortex rise
10. counter-rotating propellers
11. active (feedback) distributed body vorticity control systems.

For a new platform design all of the techniques discussed herein, along with various combinations (e.g., ref. 181, combination of turbulence enhancement and vortex merging for tip vortices) should be at least considered in the preliminary design stage.

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| 16. Abstract Vortex flows produced by submersibles typically unfavorably influence key figures of merit such as acoustic and nonacoustic stealth, control effectiveness/maneuverability, and propulsor efficiency/body drag. Sources of such organized, primarily longitudinal, vorticity include the basic body (nose and sides) and appendages (both base/intersection and tip regions) such as the fairwater, dive planes, rear control surfaces, and propulsor stators/tips. Two fundamentally different vortex control approaches are available (a) deintensification of the amplitude and/or organization of the vortex during its initiation process, and (b) downstream "vortex disablement." Vortex control techniques applicable to the initiation region (deintensification approach) include transverse pressure gradient minimization via altered body cross section, appendage dilllets, fillets, and sweep, and various appendage tip and spanload treatments along with use of active controls to minimize control surface size and motions. Vortex disablement can be accomplished either via use of control vortices (which can also be used to "steer" the vortices off-board), direct unwinding, inducement of vortex "bursting," or segmentation/tailoring for enhanced dissipation. Paper includes submersible-applicable vortex control technology derived from various aeronautical applications such as mitigation of the wing wake vortex hazard and fighter aircraft maneuverability at high angle of attack as well as the status of vortex effects upon, and mitigation of, nonlinear control forces on submersibles. Paper concludes with specific suggestions for submersible-applicable vortex control techniques. | | | | | |
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